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A polyphonic acoustic vortex and its complementary chords

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Abstract. Using an annular phased array of eight loudspeakers, we generate sound beams that simultaneously contain phase singularities at a number of different frequencies. These frequencies correspond to different musical notes and the singularities can be set to overlap along the beam axis, creating a polyphonic acoustic vortex. Perturbing the drive amplitudes of the speakers means that the singularities no longer overlap, each note being nulled at a slightly different lateral position, where the volume of the other notes is now nonzero. The remaining notes form a tri-note chord. We contrast this acoustic phenomenon to the optical case where the perturbation of a white light vortex leads to a spectral spatial distribution.

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1. Introduction

Within the optical regime it is now well understood that light can carry both a spin and an orbital angular momentum [1]–[3]. Whereas the spin component is associated with circular polarization, the orbital contribution arises from a helical phase structure. Such beams are characterized by a phase term $\exp(i\ell\theta)$, which gives rise to a phase singularity on the beam axis. Immediately around the phase singularity the phase fronts are helical, giving an azimuthal component to the momentum flow and hence an orbital angular momentum directed parallel to the singularity. The azimuthal momentum component means that these features are also described as vortices. For light waves in free space, the orbital angular momentum flux to energy ratio is simply $L/E = \ell/\omega$ [1], where ω is the wave angular frequency.

In contrast to this optical case, an acoustic wave in a gaseous medium is a scalar wave, has no transverse amplitude, is not therefore polarized, and hence cannot carry spin angular momentum. However, a sound wave can have a spatial phase dependence containing phase singularities [4], thereby forming phase fronts that have a local helical structure and hence carry an orbital angular momentum [5, 6]. This acoustic orbital angular momentum has been recently shown to be capable of setting physical objects into rotation [7, 8].

Prior to studies of orbital angular momentum, the existence of optical phase singularities had been extensively investigated. Initially, these investigations were in random or complicated fields [9], and later at the centre of helically phased beams [10, 11]. Phase singularities arise whenever three or more non-collinear plane waves interfere [12, 13], and hence occur in all natural light fields. This is typified by the case of laser speckle, where the singularities map out a tangle of vortex lines embedded within the field that percolate through all space [14]. However, in everyday situations, the presence of these lines of darkness goes unnoticed since, in general, the singularities of each spectral component do not overlap.

In special cases, it is possible to form white-light (temporally incoherent) optical beams in which vortex lines from all spectral components overlap, giving a single black vortex line along the beam axis [15]–[18]. If these beams are then perturbed, the vortex lines associated with each spectral component move apart and, within the transverse cross-section, each wavelength has its own singularity. At any of these singularities all other wavelengths are present, giving a characteristic spatial spreading of complementary colours [15], [19]–[22].

Of course, the phenomena of phase singularities, vortices and angular momentum apply not just to light, but to all types of wavefield. In this paper, we report the use of an annular phased array of loudspeakers arranged around a ring to form polyphonic acoustic vortices with phase singularities at their centre. Software control of these speakers allows us to address each of them with an arbitrary mix of acoustic frequencies, in our case corresponding to four different musical notes. By setting the complex amplitude of each speaker, we can create a polyphonic acoustic vortex, with suppression of the sound intensity at a singularity of 45 dB. For a low-intensity beam, this suppression is sufficient to observe the noise floor of the measurement system in the centre of the vortex beam. Subsequent perturbation of the amplitudes driving the individual speakers splits the vortex and creates separated singularity positions for each acoustic frequency. At each of these positions one of the notes is cancelled, leaving the remaining three notes to form a tri-note chord.

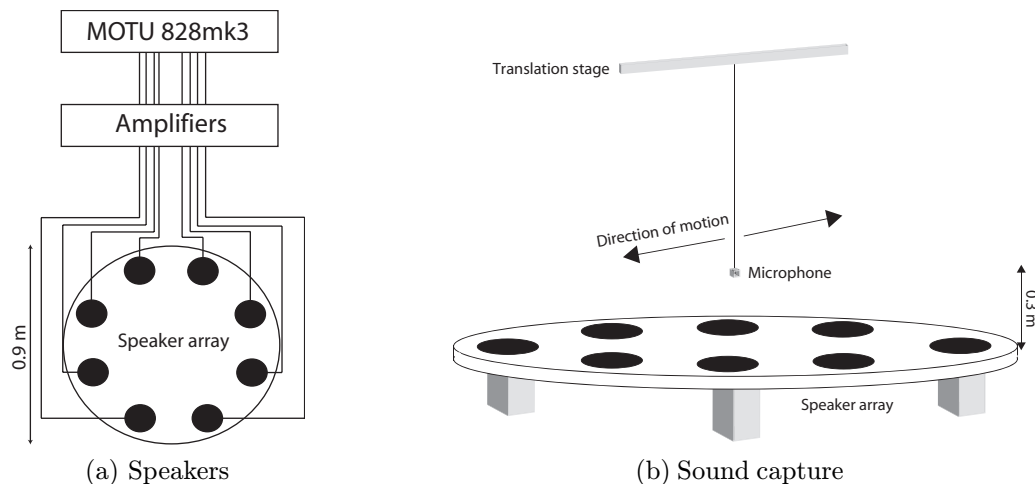


Figure 1. Experimental apparatus: eight 0.08 m diameter loudspeakers, configured in a circular array 0.9 m in diameter.

2. Apparatus

To form acoustic vortices, eight 0.08 m diameter loudspeakers, with an impedance of $8\ \Omega$, were mounted in a ring approximately 0.9 m in diameter (see figure 1(a)). The speaker array was acoustically isolated from the laboratory environment by mounting within a cylindrical housing coated in a double layer of lead-lined foam. Each speaker was driven by its own amplifier ($\pm 15\text{ V}$), which take their input signals from an eight-channel digital sound card (Motu 828mk3 firewire audio interface). The digital sound card produced eight time synced independent wavetrains. Figure 1(b) shows the microphone (Knowles Electronics FG-23329-P07) suspended from a motorized translation stage such that it can be traversed across the centre of the array, approximately 0.3 m above the speakers. Although the microphone design is not well calibrated to measure absolute sound levels, its compact size (5 mm) and nominal sensitivity -53 dB(V/0.1 Pa) make it ideal for sensitive measurements without unduly perturbing the sound field. The output from the microphone is fed via a low-noise amplifier (Laser Components (UK) Ltd, model: DLPVA-100-B-S) to the digital acquisition card for spectral analysis. In all cases, the gain of this amplifier is set to best match the dynamic range of measured voltages to the dynamic range of the data acquisition board.

3. The experiment

3.1. Polyphonic vortex beam

As in our previous acoustic work [8], all eight speakers were driven with the same frequency and the same magnitude. By increasing the relative phase delay between adjacent speakers of $\pi/4$, a good approximation to an acoustic vortex with $\ell = 1$ is created. In our previous work, the phase shifts were based on analogue circuitry, but this approach became highly complicated in the multitonal case, hence our use of the digital sound card.

Initially using a single frequency of 523 Hz, we measured the relative sound levels across the diameter of the acoustic vortex beam. As with our previous work [8], similar cross-sections

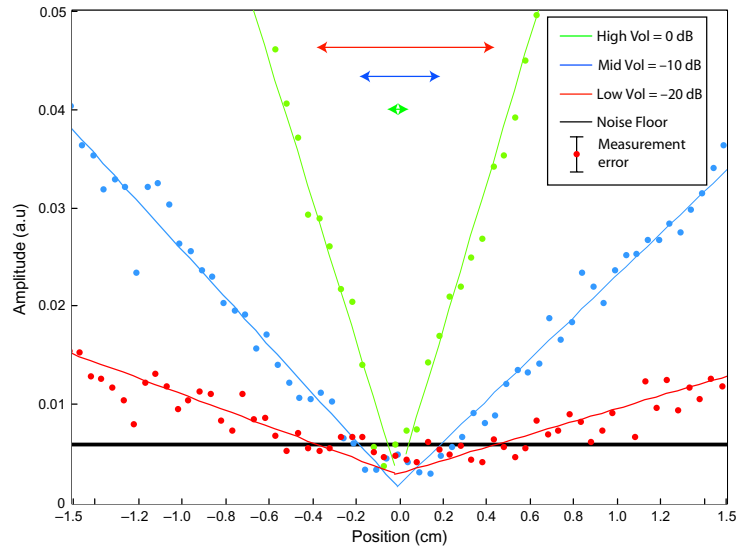


Figure 2. Amplitude cross-section through the acoustic vortex at 523 Hz, recorded for three different sound volumes. The points are experimentally recorded data, the solid lines are linear best fits (not constrained to pass through zero), and the horizontal arrows mark the extent over which the noise of the measurement system dominates over the measured signal.

are obtained by scanning in any orientation through the vortex core. The length of our translation stage limited the range of these scans to 60 mm on either side of the beam centre. In the region of the singularity, one expects the intensity to scale with $r^{|2\ell|}$. At high drive voltages, the acoustic signal dominates over the noise from the microphone and the singularity appears as a point in the cross-section. Reducing all the speaker drive voltages by an order of magnitude means that the recorded signal near the singularity falls below the noise floor of the microphone. This gives an extended area in the middle of the beam within which the measurement noise dominates over the signal; see figure 2. Note that as the volume is reduced, the area over which the noise dominates increases. This noise core is of similar origin to that predicted, also for the acoustic case by Berry and Dennis [23]. In their case, the predicted radius of this core was based on a calculation of the ultimate noise floor resulting from the Brownian motion of the air molecules, a sensitivity that cannot be obtained using a conventional microphone.

For the polyphonic vortex, we defined four different frequencies 329, 392, 440 and 523 Hz, which correspond to musical notes E, G, A and C. During the initial set-up, we addressed each speaker with each tone in sequence, adjusting the drive voltage so that the volume recorded by the centrally positioned microphone was the same. These 32 individual amplitudes were then used to drive the eight speakers, producing four superimposed acoustic vortices. In practice, we found that even when set up in this manner, the vortices at the different frequencies were misaligned from the beam axis by a few millimetres and a further software adjustment was required to steer each of the vortices so that the phase singularities coincided precisely with the centrally positioned microphone. The drive voltage to each speaker was again adjusted to be near the maximum permitted, ensuring that most measurements were made well above the noise floor of the microphone. The voltage $V(\nu)_N$, of the ν frequency component, driving the

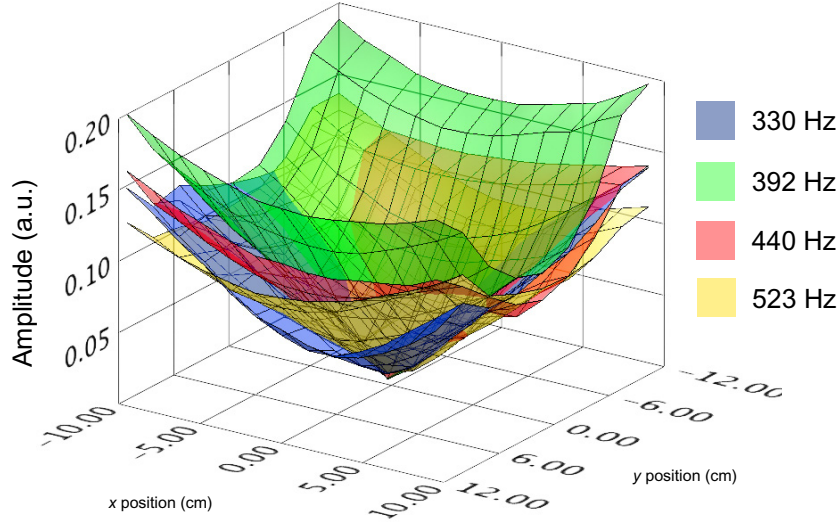


Figure 3. 2D plots of amplitudes corresponding to the four frequency components of the polyphonic acoustic vortex. Note that the zero-amplitude singularities all overlap in the centre of the beam.

N th speaker at azimuthal position θ_N , is given by

$$V(\nu)_N = A(\nu)(1 + \delta x_\nu \sin \theta_N + \delta y_\nu \cos \theta_N) \sin(2\pi \nu t), \quad (1)$$

where $A(\nu)$ sets the relative amplitude of the vortex field at frequency ν . Adjusting the coefficients δx_ν and δy_ν for each spectral component allowed the position of the vortex at that frequency to be moved in the transverse plane so that the different frequency components overlapped on the beam axis.

In addition to producing the wavetrains to drive the loudspeakers, the same computer was used to control the translation stage on which the microphone was mounted, record the microphone output and analyse its frequency spectrum. Figure 3 shows a 2D cross-sectional scan of the amplitude of the four frequencies. Figure 4 shows the 1D amplitude cross-section through the polyphonic acoustic vortex and figure 5 shows the corresponding spectral plots. The linear variation (in amplitude) corresponds to an acoustic intensity scaling with the square of the radius, as would be expected for an $\ell = 1$ vortex. The lines vary slightly in gradient from each other, indicating that away from the vortex the sound beams may well be slightly asymmetric. Compared with the equivalent plane wave (obtained by setting all the relative phases to zero), the intensity suppression at the centre of the vortex beam is of order 45 dB, limited only by the measurement sensitivity of the microphone. The measured spectral analysis is also shown for two different radii. The residual spectral signals at the central singularity most probably arise from slight nonlinearities in the drive electronics.

3.2. Perturbing the vortex

Having established that it is possible to form a polyphonic vortex, it is natural to examine whether this can be perturbed and how this contrasts to the optical case. In the optical case, although the spectrum is continuous, the perception of colour is highly complex. At a simplistic

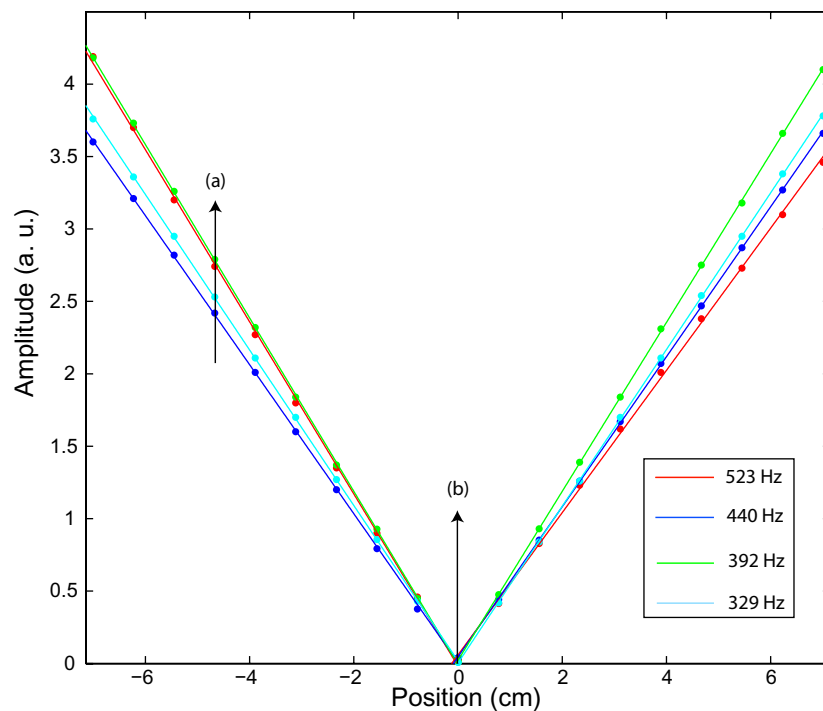


Figure 4. Amplitude cross-section of the polyphonic vortex recorded at much higher volume than shown in figure 2. The points show the experimental data and the solid line shows the best linear fit. (a) and (b) indicate the off- and on-axis positions for which the full spectral signals are shown in figure 5.

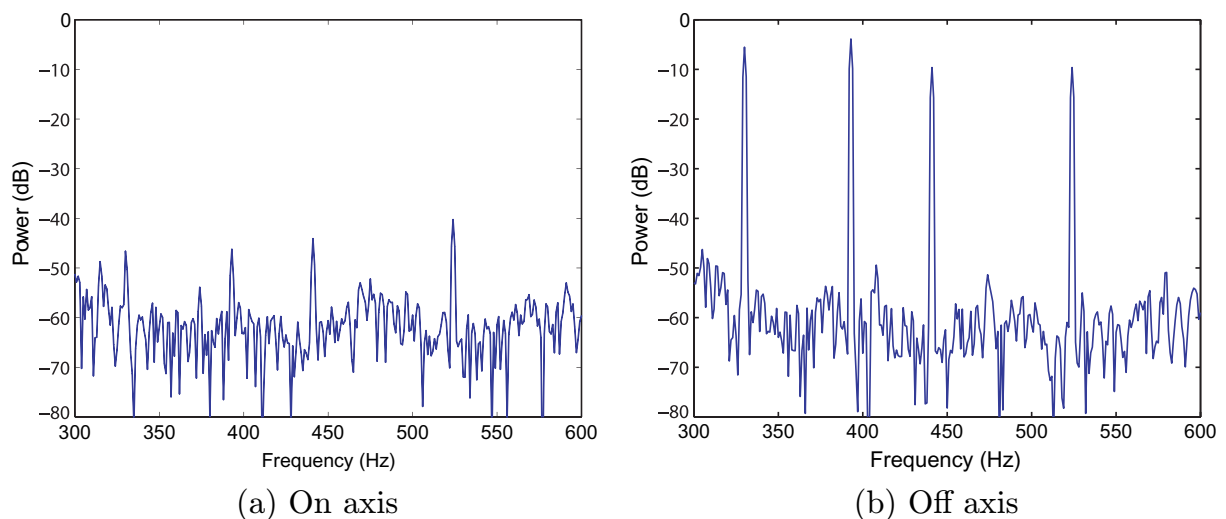


Figure 5. Spectral plots of the microphone signal recorded at the off- (a) and on- (b) axis positions of figure 4.

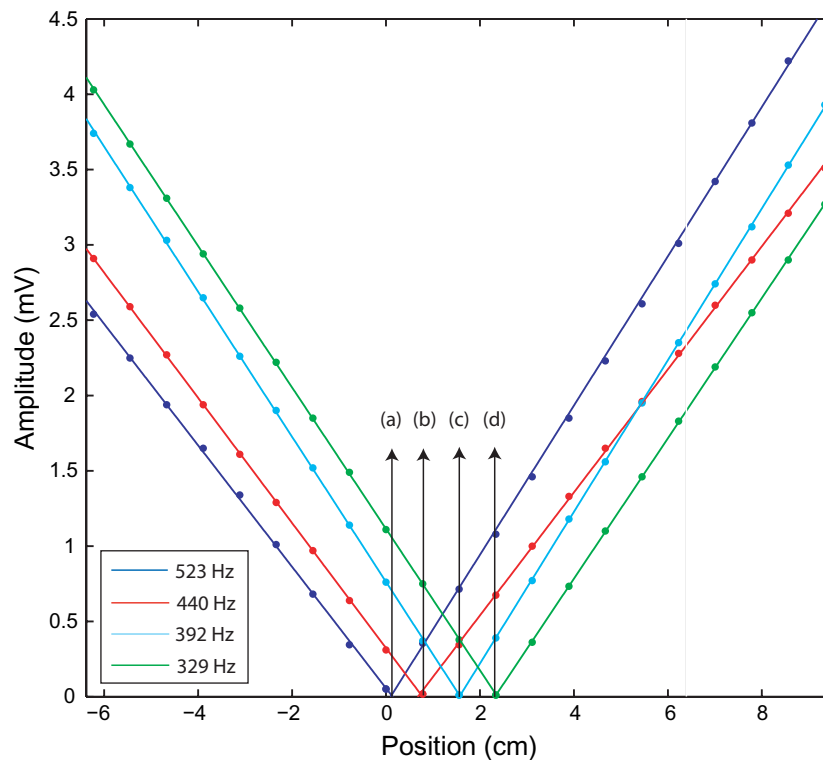


Figure 6. Perturbation of the vortex components. The four arrows indicate the positions of the complementary chords of the vortex, and a spectral analysis was made of each point. The results of this analysis can be seen in figure 7.

level, it can be approximated by stimulation of red, green and blue receptors (or their electronic equivalent). When any one of the red, green or blue stimulations are absent, then one perceives a complementary colour, i.e. cyan, magenta or yellow. Indeed in the vicinity of a perturbed white light vortex, these complementary colours give a characteristic spatial spectral image [15, 20].

The perception of sound is very different from that of light. Rather than the visual recording of a spatial pattern in three spectral bins, the ear is capable of resolving many acoustic frequencies simultaneously, albeit at one single point. Of course, a series of point measurements can be combined to form an image and, furthermore, certain combinations of notes are more usually described as a chord. In analogy to the experiments we performed in the optical case [15], we can perturb the acoustic vortex to separate the precise position of the phase singularities for different frequencies. We slightly adjusted δx_v and δy_v for each frequency component such that the acoustic vortices for each note were separated from each other by a few millimetres. Scanning the microphone across the acoustic beam revealed the splitting of the singularities into their spectrally specific positions; see figure 6. We note that the applied perturbation causes some distortion of the form of the beam at larger radii, manifest by a crossing of the straight line fits, indicating a slight beam asymmetry. However, perturbing the vortices in this way does not seem to affect the depth of the intensity null of the vortices themselves. By positioning the microphone at any one of these singularities, it detected only the other three notes and hence the chords comprising G, A, C or E, A, C or E, G, C or E, G, A. These multiple frequency stimuli are analogous, but obviously not identical, to the

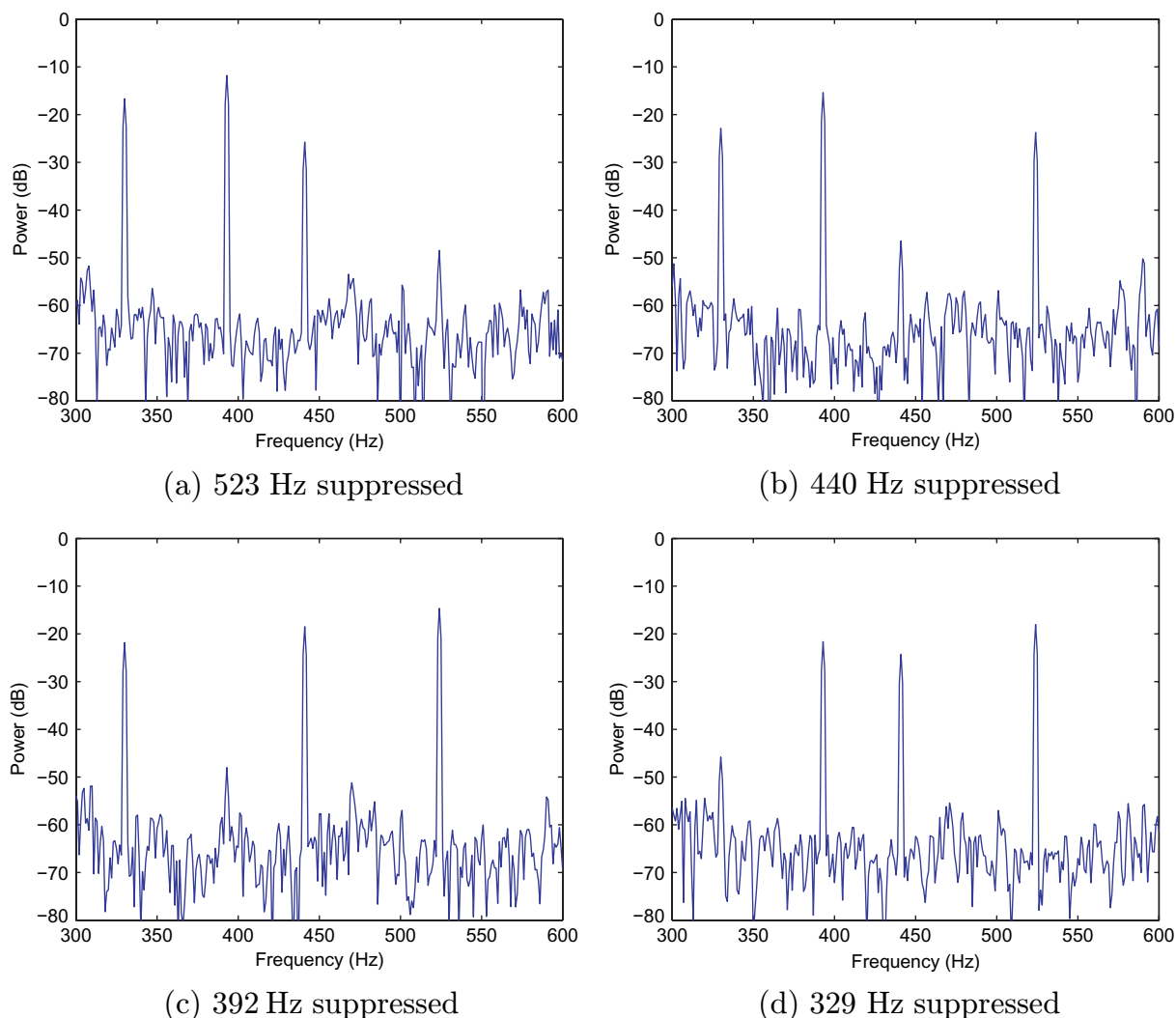


Figure 7. Spectral plots of the perturbed vortex at the point of suppression of each note.

complementary colours comprising multiple wavelengths; hence we term them complementary chords, whose corresponding acoustic spectra are shown in figure 7.

4. Conclusions

We have demonstrated that it is possible to produce helically phased sound beams containing multiple frequencies with their phase singularities all aligned to the beam axis—a polyphonic acoustic vortex. Suppression of the on-axis sound intensity can exceed 45 dB, limited primarily by our measurement noise. Although this degree of suppression is significant, it is not sufficient to reach the Brownian noise floor and to reveal the thermodynamic core predicted previously [23]; it is, however, sufficient to reveal the noise floor of the measurement system.

Perturbation of the polyphonic vortex spatially separates the singularities. At each singularity, the remaining frequencies form a complementary musical chord. The ability to form

and measure complicated patterns of vortex lines in sound suggests that, by analogy with the optical cases, it should be possible to form the acoustic equivalent of optical knots [24, 25] and non-integer vortices [26, 27], and to study the fractal structure of singularity lines embedded within random acoustic fields created by reflection and scatter, the latter occurring on the scale of the wavelength.

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